A Simplified Model of ADAF with the Jet Driven by the Large-Scale Magnetic Field

Yang Li, Zhao-Ming Gan and Ding-Xiong Wang[1]

School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract

We propose a simplified model of outflow/jet driven by the Blandford-Payne (BP) process from advection dominated accretion flows (ADAF) and derive the expressions of the BP power and disk luminosity based on the conservation laws of mass, angular momentum and energy. We fit the 2–10 keV luminosity and kinetic power of 15 active galactic nucleus (AGNs) of sub-Eddington luminosity. It is found that there exists an anti-correlation between the accretion rate and the advection parameter, which could be used to explain the correlation between Eddington-scaled kinetic power and bolometric luminosity of the 15 samples. In addition, the Ledlow-Owen relation for FR I/II dichotomy is re-expressed in a parameter space consisting of logarithm of dimensionless accretion rate versus that of the BH mass. It turns out that the FR I/II dichotomy is determined mainly by the dimensionless accretion rate, being insensitive to the BH mass. And the dividing accretion rate is less than the critical accretion rate for ADAFs, suggesting that FR I sources are all in the ADAF state.

Key words: galaxies: jets - black hole physics - accretion, accretion disk - magnetic fields
PACS: 97.60.Lf, 04.70.-s, 98.62.Mw, 95.30.Sf

1 INTRODUCTION

Advection-dominated accretion flow (ADAF) is widely regarded as a successful model for explaining the quiescent and hard states of black hole (BH) X-ray binaries as well as low-luminosity AGNs (Narayan 2005, Yuan 2007,

---

[1] Corresponding author. Tel: +862787540742; fax: +862787542391
E-mail address: dxwang@mail.hust.edu.cn (D.-X. Wang).

and Ho 2008 for reviews). It have been predicted theoretically and confirmed in numerical simulations that strong winds and jets can be driven by the tremendous thermal energy in ADAF (see Narayan & McClintock 2008 and references therein). Observational evidence for the association of nonthermal relativistic jets with ADAFs has been accumulated in recent years with the discovery of radio emission in virtually every BH binaries in the hard state and in low-luminosity AGNs (Corbel et al. 2000; Fender 2001; Fender, Belloni & Gallo 2004; Fender & Belloni 2004).

It has been pointed out that an outflow emanating from an accretion disk can act as a sink for mass, angular momentum and energy, altering the dissipation rates and effective temperatures across the disk (Donea & Biermann 1996; Knigge 1999; Kuncic & Bicknell 2007; Li et al. 2008; Xie & Yuan 2008). Thus the jets launched from the ADAFs should influence the dynamics of ADAFs due to the mass, angular momentum and energy extracted through outflow.

The currently most favored mechanisms for jet production include the Blandford-Znajek (BZ) process (Blandford & Znajek 1977) and the Blandford-Payne (BP) process (Blandford & Payne 1982, hereafter BP82). In the BZ process, energy and angular momentum are extracted from a rotating BH and transferred to a remote astrophysical load by open magnetic field lines. In the BP process, the magnetic fields threading the disk extract energy from the accretion disk itself to power the jet/outflow. Some authors argued that the maximal jet power extracted via the BP process dominates over the power extracted via the BZ process, provided that the poloidal field threading the BH is not significantly greater than that threading the inner disk (e.g., Livio et al. 1999; Meier 1999, 2001; Cao 2002; Nemmen et al. 2007). Young et al. (2007) discovered the large rotating wind of the quasar PG 1700+518, providing direct observational evidence that outflows from AGNs is launched from the disks.

Merloni & Heinz (2007, hereafter MH07) obtained a clear relationship between Eddington-scaled kinetic power and bolometric luminosity based on a statistical analysis of a sample of 15 sub-Eddington AGNs. The measured slope suggests that these objects are in a radiatively inefficient accretion mode. And they interpreted this fact with a simple coupled accretion-outflow disk model. However, dynamically important magnetic fields and their role in the jet production mechanisms were not taken into account in MH07.

Fanaroff & Riley (1974) recognized that the majority of radio galaxies can be classified into two types (FR I and FR II) according to their radio morphology, i.e., edge darkened and edge brightened sources, and that this division rather neatly translates into a separation in radio power being below and above $L_{178} \simeq 2.5 \times 10^{33} h_{50}^{-2}$ erg s^{-1} Hz^{-1} at 178 MHz. This division has

become even clearer and sharper when it has been found by Ledlow & Owen (1994, 1996) that it is clearly shown by a line in the plane of the optical luminosity of the host galaxy and the total radio luminosity. Over the years, much work has been done to understand the remarkable FR I/II dichotomy, which may depend on the fundamental parameters, such as BH spin and accretion mode (Meier, 1999; Ghisellini & Celotti, 2001, hereafter GC01); Wold, Lacy & Armus 2007, hereafter WLA07; Wu & Cao 2008, hereafter WC08).

Motivated by the above work, we intend to discuss the outflow/jet driven by the BP process, and investigate the interaction of the outflow/jet with ADAF. For simplicity we treat a Schwarzschild BH, and the BZ process is not included in this model. Following Yuan, Ma & Narayan (2008, hereafter YMN08), we replace the radial momentum equation by a simple algebraic relation between the angular velocity of the gas and the Keplerian angular velocity of the disk. Based on the conservation laws of mass, angular momentum and energy we derive the expressions of the BP power and disk luminosity. We fit the 2–10 keV luminosity and kinetic power of the 15 samples given in MH07 based on ADAF model with jet, and obtain an anti-correlation between the accretion rate and the advection parameter, which could be used to explain the correlation between Eddington-scaled kinetic power and bolometric luminosity of the 15 samples. In addition, we express the dividing line of the Ledlow-Owen relation for FR I/II dichotomy in the plane of $\lg \dot{m}_H$ versus $\lg M_{BH}$. We find that the FR I/II dichotomy is closely related to the accretion rate, but has a weak dependence on the BH mass, which is consistent with the results derived by GC01 and WLA07. And the dividing accretion rate is less than the critical accretion rate for ADAFs, suggesting that FR I sources is in the ADAF state.

This paper is organized as follows. In Sect. 2 we describe our model, and derive the expressions for the BP power and disk luminosity at the presence of a jet based on the conservation laws of mass, angular momentum and energy. In Sect. 3, we fit the 2–10 keV luminosity and kinetic power of the 15 sources given in MH07 based on our model. In Sect. 4 we present the dividing lines of the Ledlow-Owen relation for FR I/II dichotomy in the plane of $\lg \dot{m}_H - \lg M_{BH}$. Finally, in Sect. 5, we summarize our main conclusions.

2 MODEL DESCRIPTION

We assume that the ADAF is stationary and axisymmetric, extending from the outer edge to the BH horizon. Two kinds of magnetic fields are involved in this model, i.e., the large-scale magnetic field threading the ADAF and the small-scale magnetic field tangled in the ADAF. The large-scale and the small-scale magnetic fields are assumed to work independently, contribute to

the BP process and viscosity, respectively. The ADAF is assumed to be ideally conducting and force-free.

Following BP82, we assume that the poloidal magnetic field on the disk surface varies with the disk radius as follows,

$$B_{ADAF} = B_H \left(r/r_H \right)^{-5/4},$$ (1)

where r and r_H are the ADAF and horizon radii, respectively, and we have $r_H = 2r_g$ with $r_g = GM/c^2$ for a Schwarzschild BH. The quantities B_{ADAF} and B_H are the magnetic field at ADAF and horizon, respectively.

Considering the balance between the magnetic pressure on the horizon and the ram pressure of the innermost parts of ADAF, Moderski, Sikora & Lasota (1997) expressed the magnetic field at the horizon as follows,

$$B_H^2 c \Big/ 8\pi = P_{ram} \sim \rho c^2 \sim \dot{M}_H c^2 \Big/ \left(4\pi r_H^2 \right),$$ (2)

where $\dot{M}_H$ is the accretion rate at the BH horizon, which can be written as a dimensionless one in terms of the Eddington accretion rate as follows,

$$\dot{m}_H = \dot{M}_H \Big/ \dot{M}_{Edd},$$ (3)

where

$$\dot{M}_{Edd} = 1.4 \times 10^{18} M_{BH}(M_\odot) \left(g \cdot s^{-1} \right).$$ (4)

Considering that equation (2) is uncertain, we introduce a parameter λ to adjust the magnetic pressure at the BH horizon relative to the ram pressure of ADAF, and equation (2) is rewritten as

$$\dot{M}_H c = \lambda B_H^2 r_H^2.$$ (5)

As argued by BP82 and Spruit (1996), the outflow matter could be accelerated centrifugally along the magnetic field lines, overcoming a barrier of gravitational potential to form magnetohydrodynamic (MHD) jets. The Poynting flux dominates over the kinetic flux near the disk surface, and the former is converted into the latter during accelerating matter in the outflow. Thus we express the Poynting energy flux S_E extracted electromagnetically from the ADAF as (The derivation of equation (6) is given in Appendix A),

$$S_E = \frac{B_{ADAF}^2 \Omega^2 r^2}{4\pi c}.$$ (6)

The electromagnetic angular momentum flux S_L extracted is related to the Poynting energy flux by

$$S_L = S_E/\Omega = \frac{B_{ADAF}^2 \Omega r^2}{4\pi c}. \tag{7}$$

The energy flux of the jet can be regarded as the sum of the kinetic and the Poynting fluxes,

$$F_{jet} = \frac{1}{2}\dot{M}_{jet}\left(\Omega^2 r^2 + v_P^2\right) + S_E = F_K + S_E, \tag{8}$$

where $\dot{M}_{jet}$ is the mass loss rate in the jet from unit area of the ADAF, and v_P is the poloidal velocity of the outflow, and F_K is the kinetic flux.

It is noted that F_K is much less than S_E at the surface of ADAF, while the two are comparable at Alfven surface due to a considerable fraction of the Poynting flux converted into kinetic flux. Thus the energy flux of the jet is related to $\dot{M}_{jet}$ by

$$F_{jet} = \Gamma_j \dot{M}_{jet} c^2, \tag{9}$$

where Γ_j is the bulk Lorentz factor of the jet.

Considering that F_{jet} is dominated by S_E at the surface of ADAF, and combining equations (1), (5), (6), (8) and (9), we derive the relation between $\dot{M}_{jet}$ and $\dot{M}_H$ as follows,

$$\dot{M}_{jet} = \dot{M}_H r_H^{0.5} r^{-0.5} \Omega^2 \left/ \left(4\pi\lambda\Gamma_j c^2\right)\right.. \tag{10}$$

Inspecting equation (10), we find that the ratio of $\dot{M}_{jet}$ to $\dot{M}_H$ is sensitive to and inversely proportional to the value of the parameter λ.

Based on the self-similar solution obtained by Narayan & Yi (1994) YMN08 suggested a simple algebraic relation between the angular velocity of ADAF and the Keplerian angular velocity as follows,

$$\Omega = f\Omega_K, \tag{11}$$

where the quantity f is a function of the radius r expressed as follows,

$$f = \begin{cases} f_0, & \text{for } r \geq 6r_g, \\ f_0 3\,(r - 2r_g)/2r, & \text{for } r < 6r_g, \end{cases} \tag{12}$$

In equation (12) f_0 is an adjustable constant. As argued in YMN08, $f_0 = 0.33$ gives very good results for all accretion rates as the viscous parameter α is large, say ~ 0.3, for which an ADAF solution is possible. Although the global solutions of ADAF with large-scale magnetic field have not been achieved, we think equations (11) and (12) could be applicable to ADAF with jet driven by the BP process. We expect that the values of the function f are less than those given by equation (12), and $f_0 = 0.33$ can be regarded as an upper limit in calculations.

Incorporating equations (10), (11) and (12), we have the dimensionless mass flux of the jet as follows,

$$
\begin{aligned}
\dot{m}_{jet}(\lambda, \Gamma_j, \xi) &= \dot{M}_{jet}\left(4\pi r_g^2 \big/ \dot{M}_H\right) \\
&= \frac{2f_0^2 \xi_H^{0.5}}{\lambda \Gamma_j} \xi^{-3.5} \times
\begin{cases}
1, & \text{for } \xi \geq 6, \\
\left[3\left(\xi - 2\right)/2\xi\right]^2, & \text{for } \xi < 6,
\end{cases}
\end{aligned}
\tag{13}
$$

where $\xi \equiv r/r_g$ is the radial parameter of the disk defined in terms of the radius r_g.

Based on equation (13) we have the curves of the dimensionless jet mass flux $\dot{m}_{jet}$ varying with the parameter ξ for the given values of Γ_j as shown in Figure 1.

As shown in Figure 1, the dimensionless jet mass flux $\dot{m}_{jet}$ increases with ξ at first, and then it decreases steeply with ξ as $\dot{m}_{jet} \propto \xi^{-3.5}$, attaining its peak value in the region $r < 4r_g$. This result implies that the outflow is launched predominantly from the innermost ADAF.

Inspecting equation (13) and Figure 1, we find that the dimensionless mass flux of the jet at the given radius decreases significantly with the increasing Γ_j, and we have $\dot{m}_{jet} \to 0$ for $\Gamma_j \to \infty$. This result implies that the extracted energy from the disk is almost carried in the form of electromagnetic form, suggesting the presence of a strong mass loss in the case that the bulk Lorentz factor is small enough.

According to the conservation law of mass, the accretion rate of disk matter is related to the mass outflow rate by

$$
d\dot{M}_{acc}(r)\big/dr = 4\pi r \dot{M}_{jet}.
\tag{14}
$$

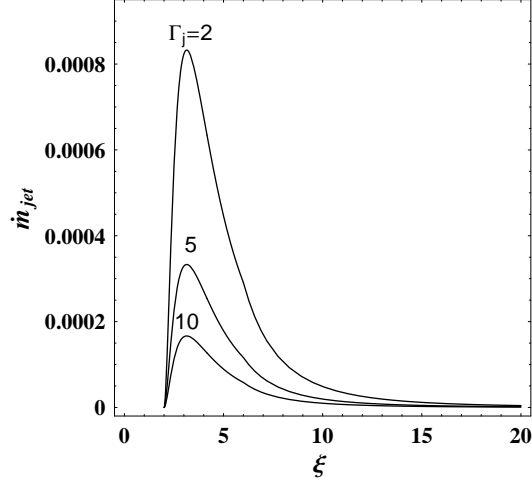Incorporating equations (13) and (14), we have the dimensionless accretion

Fig. 1. The curves of $\dot{m}_{jet}$ versus ξ for different values of Γ_j with $\lambda=0.5$.
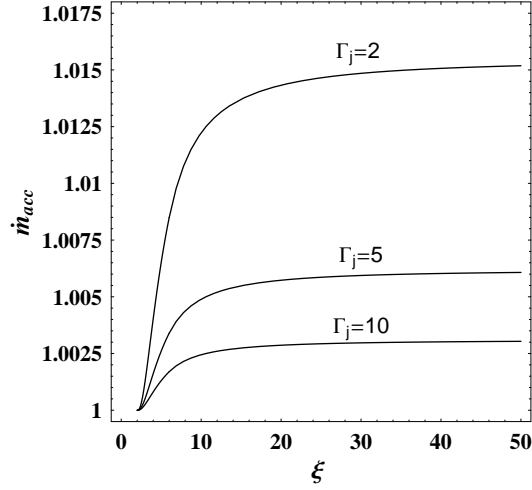

Fig. 2. The curves of $\dot{m}_{acc}$ versus ξ for different values of Γ_j with $\lambda=0.5$.

rate as follows,

$$\dot{m}_{acc}(\lambda,\Gamma_j;\xi) = \dot{M}_{acc}\Big/\dot{M}_H = 1 + \int\limits_{\xi_H}^{\xi} \xi'\dot{m}_{jet}(\lambda,\Gamma_j,\xi')d\xi'. \qquad (15)$$

By using equation (15) we have the curves of $\dot{m}_{acc}$ varying with ξ for the given values of Γ_j as shown in Figure 2. It is shown that $\dot{m}_{acc}$ increases steeply with the increasing ξ in the innermost ADAF, while it almost keeps constant as r is greater than dozens of r_g.

In the BP process accreting matter is channeled into the outflow/jet by virtue of the poloidal magnetic field lines frozen in the disk, and the streaming gas is accelerated due to the work done by the magnetic torque. Thus equation of angular momentum at the presence of the jet should be written as

$$\frac{d}{dr}\left(\dot{M}_{acc}\Omega r^2\right) = -\frac{d}{dr}\left(4\pi r^2\tau_{r\varphi}H\right) + 4\pi r\left[\dot{M}_{jet}\Omega r^2 + S_L\right], \qquad (16)$$

where H and $\tau_{r\varphi}$ are respectively the vertical scale height and rϕ-component of stress tensor, and they read (Manmoto, Mineshige & Kusunose 1997)

$$H = c_s/\Omega_K = \sqrt{P/\rho}\Big/\Omega_K, \ \tau_{r\varphi} = -\alpha P, \qquad (17)$$

where $c_s, \quad P$ and ρ are the isothermal sound speed, total pressure and height-averaged density, respectively. Substituting equations (14) and (17) into equation (16), we have

$$\sqrt{\frac{P^3}{\rho}} = \frac{\sqrt{r_g c^2}}{4\pi\alpha r^{3.5}}\left[\int_{r_H}^{r}\dot{M}_{acc}(r)\frac{d}{dr}\left(\Omega r^2\right)dr - \int_{r_{in}}^{r}4\pi r S_L dr\right], \qquad (18)$$

where 'no torque boundary condition' at the horizon of a Schwarzschild BH is used in deriving equation (18).

As given by Narayan & Yi (1994), the parameter δ indicates advection-dominated degree of the flow, and we have the disk luminosity by integrating the energy equation as follows,

$$L_{disk} = (1-\delta)\int_{r_H}^{r_{out}}\tau_{r\varphi}r\left(d\Omega/dr\right)4\pi r H dr = (1-\delta)\int_{r_H}^{r_{out}}6\pi\alpha f r\sqrt{P^3\Big/\rho}\,dr. (19)$$

Substituting equation (18) into equation (19), we express the disk luminosity of ADAF as

$$L_{disk} = 1.5 \times \sqrt{r_g c^2}\,(1-\delta) \\ \times \int_{r_H}^{r_{out}}\frac{f}{r^{2.5}}\left[\int_{r_H}^{r}\dot{M}_{acc}(r')\frac{d}{dr'}\left(\Omega r'^2\right)dr' - \int_{r_H}^{r}4\pi r'S_L dr'\right]dr, \qquad (20)$$

where the first term in the bracket at the right-hand side represents the releasing rate of the accreting matter's energy, and the second integral is the cooling rate due to the outflow/jet driven by the BP process.
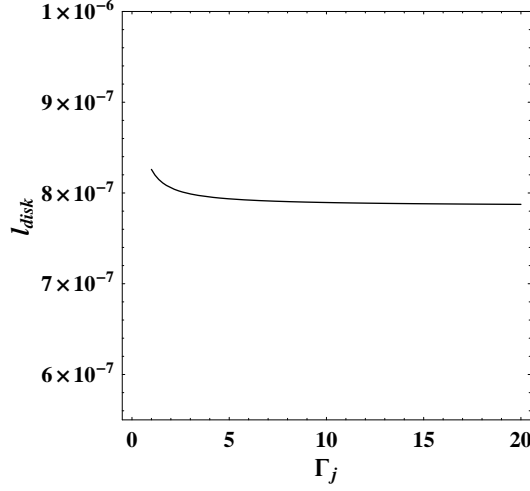
8

Fig. 3. The curves of l_{disk} versus Γ_j with λ=0.5 for $\dot{m}_H = 0.01$, $\delta = 0.99$ and $\xi_{out} = 10^5$.

Substituting equations (1), (3), (5), (7), (11) and (18) into equation (20), we express the dimensionless disk luminosity as follows,

$$
\begin{aligned}
l_{disk} = L_{disk}\Big/ \dot{M}_{Edd}c^2 &= 1.5 \times \dot{m}_H(1 - \delta) \\
&\times \int_{\xi_H}^{\xi_{out}} \frac{f}{\xi^{2.5}} \left[\int_{\xi_H}^{\xi} \dot{m}_{acc}(\lambda, \Gamma_j, \xi') \frac{d}{d\xi'} \left(f\xi'^{0.5} \right) d\xi' - \frac{1}{\lambda} \int_{\xi_H}^{\xi} 2\xi_H^{0.5} f\xi'^{-1} d\xi' \right] d\xi.
\end{aligned} \tag{21}
$$

Four parameters, Γ_j, $\dot{m}_H$, λ and δ are involved in equation (21) for the disk luminosity l_{disk}. In fact l_{disk} is determined mainly by the parameters $\dot{m}_H$, λ and δ, being insensitive to the Lorentz factor Γ_j as shown in Figure 3. According to the observations of AGNs given by some authors (Urry & Padovani 1995; Biretta, Sparks & Macchetto 1999), we take the typical value, $\Gamma_j = 10$, for calculating jets in this paper.

By using equations (9) and (11) the jet power driven by the BP process is expressed as

$$
Q_{jet} = \int_{r_H}^{r_{out}} \Gamma_j \dot{M}_{jet} c^2 4\pi r dr = \dot{M}_H r_H^{0.5} \lambda^{-1} \int_{r_H}^{r_{out}} r^{0.5} \Omega^2 dr. \tag{22}
$$

Inspecting equation (22), we find that the jet power depends on the accretion rate at the innermost ADAF, the parameter λ and the angular velocity of the accretion flow. Since $\dot{M}_H$ and λ expressed by equation (5) is related to the magnetic field strength at the horizon, and Ω is linked to accretion mode, the jet power is expected to be related to these two factors.

9

Substituting equations (5), (11) and (12) into equation (22), we have the dimensionless jet power expressed by

$$q_{jet} = Q_{jet} \Big/ \dot{M}_{Edd} c^2$$
$$= 2\dot{m}_H f_0^2 \xi_H^{0.5} \lambda^{-1} \left[\int_{\xi_H}^6 \xi^{-2.5} \frac{9}{4} \left(\frac{\xi-2}{\xi} \right)^2 d\xi + \int_6^{\xi_{out}} \xi^{-2.5} d\xi \right]. \tag{23}$$

3 FITTING JET POWERS AND X-RAY LUMINOSITIES OF A SAMPLE OF AGNS

It is shown in MH07 that a clear correlation exists between Eddington-scaled kinetic power and bolometric luminosity of 15 sub-Eddington AGNs. The measured slope suggests that these objects are in a radiatively inefficient accretion mode. Based on Kuncic & Bicknell (2004) a simple coupled accretion-outflow disk model was presented to explain the main features of the observed sample. However, dynamically important magnetic fields and their role in the jet production mechanisms were not taken into account in MH07. We intend to fit the 2–10 keV luminosity and kinetic power of the 15 samples based on our model.

Inspecting equation (21), we find that the radiation flux at the presence of the jet could become negative for λ less than a critical value, and we obtain $\lambda_{\min} = 0.447$ by setting the minimum radiation flux equal to zero.

Narayan & Yi (1995) suggested that there is a theoretical upper limit on the accretion rate for an ADAF. The optically thin ADAF does not exist, and it transits to an optically thick disk for the accretion rate greater than a critical one. The exact value of the critical accretion rate is still unclear, depending on the viscosity parameter α, i.e. $\dot{m}_{crit} \simeq 0.28\alpha^2$ (Mahadevan 1997). In our model we take $\dot{m}_{crit} \simeq 0.0252$ with $\alpha = 0.3$. Combining equation (23) with the relation $\dot{m}_H \leq \dot{m}_{crit}$, we have each maximum $\lambda_{\max}$ in fitting the jet power of each source.

According to MH07, for all objects in the sample, the BH mass M_{BH} could be estimated either through the $M - \sigma$ relation or via direct dynamical measurements. As a simple analysis, the disk luminosity is related to the 2–10 keV luminosity by $L_{disk} = 5L_{2-10keV}$, and the jet power is equal to the kinetic power, $Q_{jet} = L_{kin}$. With $\lambda_{\min} = 0.447$ and $\lambda_{\max}$ for each source we derive the 2–10 keV luminosity and kinetic power of the 15 samples based on equations (21) and (23) as shown in Table 1.

From Table 1 and Figure 4 we find that most of the samples are consistent with the ADAF model except Cyg A and NGC 1275, which are marked by the

Table 1

The values of the concerned parameters for fitting the 2–10 keV luminosity and kinetic power of the 15 sub-Eddington AGNs with $\lambda_{\min}= 0.447$ and $\lambda_{\max}$, where $f_0 = 0.33$, $\alpha = 0.3$, $\Gamma_j = 10$ and $\xi_{out} = 10^4$ are assumed.

Object	$\lg M_{BH}$	$\lg L_{2-10keV}$	$\lg L_{Kin}$	$\lambda_{\min}$=0.447		$\lambda_{\max}$
				$\lg \dot{m}_H$	$\lg(1-\delta)$	$\lg(1-\delta)$
Cyg A	9.40	44.22	$45.41^{+0.19}_{-0.1}$	$-1.63^{+0.19}_{-0.1}$	$0.51^{-0.19}_{+0.1}$	$0.21^{-0.19}_{+0.1}$
NGC 507	8.90	< 39.90	$44.01^{+0.16}_{-0.26}$	$-2.53^{+0.16}_{-0.26}$	$< -2.41^{-0.16}_{+0.26}$	$< -4.41^{-0.16}_{+0.26}$
NGC 1275	8.64	43.40	$44.33^{+0.17}_{-0.14}$	$-1.95^{+0.17}_{-0.14}$	$0.77^{-0.17}_{+0.14}$	$-0.47^{-0.17}_{+0.14}$
NGC 4374	8.80	40.34	$42.59^{+0.6}_{-0.5}$	$-3.85^{+0.6}_{-0.5}$	$-0.55^{-0.6}_{+0.5}$	$-3.92^{-0.6}_{+0.5}$
NGC 4472	8.90	38.46	$42.91^{+0.14}_{-0.23}$	$-3.63^{+0.14}_{-0.23}$	$-2.75^{-0.14}_{+0.23}$	$-5.90^{-0.14}_{+0.23}$
NGC 4486	9.48	40.55	$43.44^{+0.5}_{-0.5}$	$-3.68^{+0.5}_{-0.5}$	$-1.19^{-0.5}_{+0.5}$	$-4.39^{-0.5}_{+0.5}$
NGC 4552	8.57	39.33	$42.20^{+0.14}_{-0.21}$	$-4.01^{+0.14}_{-0.21}$	$-1.17^{-0.14}_{+0.21}$	$-4.70^{-0.14}_{+0.21}$
NGC 4636	8.20	< 38.40	$42.65^{+0.11}_{-0.15}$	$-3.19^{+0.11}_{-0.15}$	$< -2.55^{-0.11}_{+0.15}$	$< -0.63^{-0.11}_{+0.15}$
NGC 4696	8.60	40.26	$42.89^{+0.22}_{-0.22}$	$-3.35^{+0.22}_{-0.22}$	$-0.93^{-0.22}_{+0.22}$	$-3.79^{-0.22}_{+0.22}$
NGC 5846	8.59	38.37	$41.86^{+0.18}_{-0.29}$	$-4.37^{+0.18}_{-0.29}$	$-1.79^{-0.18}_{+0.29}$	$-4.83^{-0.18}_{+0.29}$
NGC 6166	8.92	40.56	$43.82^{+0.5}_{-0.4}$	$-2.74^{+0.5}_{-0.4}$	$-1.56^{-0.5}_{+0.4}$	$-3.79^{-0.5}_{+0.4}$
IC 4374	8.57	41.37	$43.30^{+0.36}_{-0.26}$	$-2.91^{+0.36}_{-0.26}$	$-0.23^{-0.36}_{+0.26}$	$-0.62^{-0.36}_{+0.26}$
UGC 9799	8.58	41.89	$44.18^{+0.36}_{-0.28}$	$-2.04^{+0.36}_{-0.28}$	$-0.59^{-0.36}_{+0.28}$	$-1.97^{-0.36}_{+0.28}$
3C 218	8.96	42.17	$44.63^{+0.16}_{-0.10}$	$-1.97^{+0.16}_{-0.10}$	$-0.76^{-0.16}_{+0.10}$	$-2.03^{-0.16}_{+0.10}$
3C 388	9.18	41.69	$44.30^{+0.38}_{-0.30}$	$-2.52^{+0.38}_{-0.30}$	$-0.91^{-0.38}_{+0.30}$	$-2.90^{-0.38}_{+0.30}$

Notes: Column (1): source name; column (2): logarithm of the BH mass as derived from $M - \sigma$ relation; column (3): logarithm of the intrinsic rest-frame luminosity in the 2–10 keV band; column (4): logarithm of the kinetic luminosity; column (5): logarithm of the dimensionless accretion rate at the BH horizon with the lower limit of $\lambda_{min} = 0.447$; column (6): logarithm of $1 - \delta$ with $\lambda_{\min} = 0.447$; column (7): logarithm of $1 - \delta$ with $\lambda_{\max}$ and $\dot{m}_H = \dot{m}_{crit}$.

open circles in Figure 4 with $\lambda = 0.5$. These two sources of negative advection parameter δ are conflict with the ADAF model. As shown in column (7) of Table 1, the value of δ could be positive for NGC 1275, provided that λ is not so small. However, the negative δ cannot be removed for Cyg A.

From Table 1 and Figure 4 we find that the higher dimensionless accretion rate is apt to correspond to the greater $\lg(1 - \delta)$, implying an anti-correlation of the accretion rate $\dot{m}_H$ with the advection parameter δ. This result is consistent with the fact that there is a theoretical upper limit on the accretion rate for an ADAF: An optically thin ADAF transits to an optically thick disk
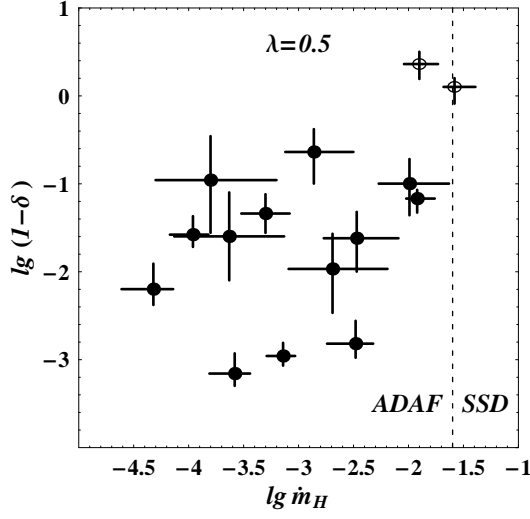
Fig. 4. The $\lg \dot{m}_H - \lg(1-\delta)$ parameter space: the values of $\lg \dot{m}_H$ and $\lg(1-\delta)$ for fitting the 2–10 keV luminosity and kinetic powers of the 15 sub-Eddington AGNs with $\lambda = 0.5$. The dashed line represents the critical accretion rate for ADAFs.

as the accretion rate reaches the critical one. This anti-correlation of accretion rate with the advection parameter δ could be used to explain the correlation between Eddington-scaled kinetic power and bolometric luminosity of the sub-Eddington AGNs.

4 THE LEDLOW-OWEN RELATION FOR FR I/II DICHOTOMY

Very recently, WC08 reproduce the dividing line of the Ledlow-Owen relation for FR I/II dichotomy, being related to the jet power and BH mass as follows,

$$\lg Q_{jet}(erg\ s^{-1}) = 1.13 \lg M_{BH}(M_\odot) + 33.42 + 1.50 \lg F. \qquad (24)$$

In equation (24) the factor F parameterizes the uncertainties of the normalization, which is constrained to be between 10 and 20 (Blundell & Rawlings 2000).

Replacing Q_{jet} in equation (24) by accretion rate given by equation (23), we have another way to express the Ledlow-Owen relation as follows,

$$\begin{aligned} \lg \dot{m}_H = {} & 0.13 \lg M_{BH}(M_\odot) - 5.68 + 1.50 \lg F \\ & - \lg \left\{ 2 f_0^2 \xi_H^{0.5} \lambda^{-1} \left[\int_{\xi_H}^{6} \xi^{-2.5} \tfrac{9}{4} \left(\tfrac{\xi-2}{\xi} \right)^2 d\xi + \int_{6}^{\xi_{out}} \xi^{-2.5} d\xi \right] \right\} \end{aligned} \qquad (25)$$
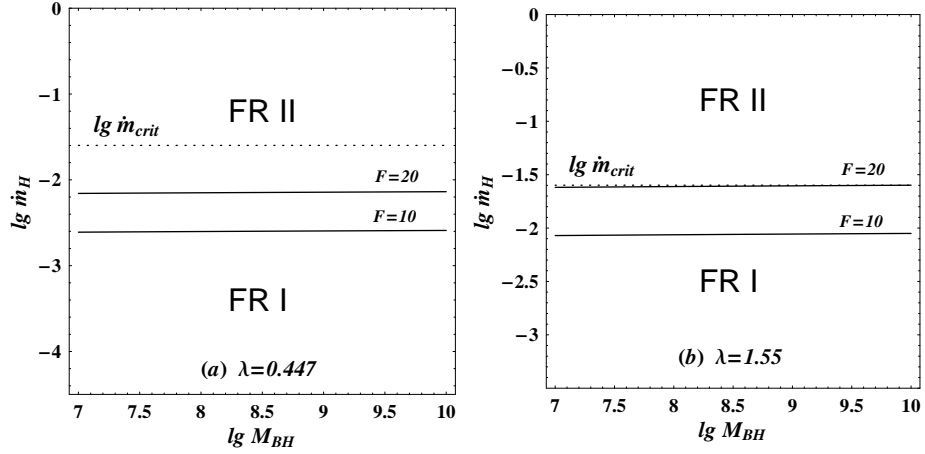
12

Fig. 5. The dividing lines for FR I/II dichotomy (solid lines) in $\lg M_{BH} - \lg \dot{m}_H$ plane with $\lambda =0.447$ and 1.55 in left and right panels, respectively. The dotted line represents the critical accretion rate for ADAFs.

There is growing evidence suggesting that most FR I type radio galaxy nuclei may possess ADAFs (Reynolds et al. 1996; Gliozzi et al. 2003; Merloni et al. 2003; Donato et al. 2004; Wu et al. 2007). This implies that the FR I/II dividing dimensionless accretion rate should be equal to or less than the upper limit of the accretion rate for ADAF. Incorporating equation (25) and the relation $\dot{m}_H = \dot{m}_{crit}$ we can derive an upper limit, $\lambda \leq 1.55$.

Based on equation (25) we have the dividing lines for FR I/II dichotomy in the plane of $\lg M_{BH}$ versus $\lg \dot{m}_H$ with $\lambda =0.447$ and 1.55 as shown in Figures 5a and 5b, respectively. It is found that the FR I/II dichotomy is determined mainly by accretion rate at the BH horizon, being insensitive to the BH mass. This result implies that FR I radio sources correspond to lower $\dot{m}_H$, whereas FR II radio galaxies have larger $\dot{m}_H$.

As shown in Figure 5, the FR I/II division can be determined by a constant $\dot{m}_H$ with the given values of the parameters F and λ. It is noted that all these dividing lines are below the dotted lines for $\lg \dot{m}_{crit}$, and this result strongly suggests that the FR I sources are in the ADAF state.

A weak BH mass dependence and a separation luminosity of about $10^{-3}-10^{-2}$ Eddington accretion rate in the FR I/II dichotomy have been found in GC01 and WLA07, and our model are consistent with these results.

13

5 SUMMARY

In this paper, we discuss the outflow/jet driven by the BP process, and investigate the interaction of the outflow/jet with ADAF. Based on the conservation laws of mass, angular momentum and energy we derive the expressions of the BP power and disk luminosity. The disk luminosity is suppressed significantly due to two reasons, (1) a fraction of accretion energy is channeled into the outflow/jet via the BP process, and (2) most of the accretion energy remaining in the gas is advected into the BH in the form of entropy.

Based on our model we fit the 2–10 keV luminosity and kinetic power of the 15 samples, and mark the points of these sources in the $\lg \dot{m}_H - \lg(1-\delta)$ parameter space. It is found that there exists an anti-correlation between the accretion rate and the advection parameter, which could be used to explain the correlation between Eddington-scaled kinetic power and bolometric luminosity of the 15 samples.

We find that the parameter λ is very important in adjusting the magnetic pressure at the BH horizon relative to the ram pressure of ADAF, and its value range can be determined by combining some theoretical consideration with the observations as argued in Sect. 3 and Sect. 4.

As a simplified model, only a Schwarzschild BH is involved, and we fail to consider the BZ process and the effects of BH spins on jet powers and disk luminosities of the AGNs. We shall improve the model in our future work.

References

Biretta, J. A., Sparks W. B., Macchetto F., 1999, ApJ, 520, 621
Blandford, R. D., Payne, D. G. 1982, MNRAS, 199, 883 (BP82)
Blandford, R. D., Znajek R. L., 1977, MNRAS, 179, 433
Blundell, K. M., Rawlings, S., 2000, AJ, 119, 1111
Cao, X. W., 2002, MNRAS, 332, 999
Corbel, S., et al. 2000, A&A, 359, 251
Donato, D., Sambruna, R. M., Gliozzi, M., 2004, ApJ, 617, 915
Fanaroff, B. L., Riley, J. M., 1974, MNRAS 167, 31p

Fender, R. P., 2001, MNRAS, 322, 31

Fender, R. P., Belloni, T., 2004, ARAA, 42, 317

Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105

Ghisellini, G., Celotti A., 2001, A&A, 379, L1 (GC01)

Gliozzi, M., Sambruna, R. M., Brandt, W. N., 2003, A&A, 408, 949

Ho, L. C., 2008, ARA&A, 46, 475

Knigge, C., 1999, MNRAS, 309, 409

Kuncic, Z., Bicknell, G. V., 2004, ApJ, 616, 669

Kuncic, Z., Bicknell, C. V., 2007, Mod. Phys. Let. A, 22,1685

Ledlow, M. J., Owen, F. N., 1996, AJ, 112, 9

Li, Y., Wang, D.-X., Gan, Z.-M., 2008, A&A, 482, 1

Livio, M., Ogilvie, G. I., Pringle, J. E., 1999, ApJ, 512, 100

Mahadevan, R., 1997, ApJ, 477, 585

Manmoto, T., Mineshige, S., Kusunose, M., 1997, ApJ, 489, 791

McKinney, J. C., 2006, MNRAS, 368, 1561

McLure, R. J., Dunlop, J. S., 2002, MNRAS, 331, 795

Meier, D. L., 1999, ApJ, 522, 753

Merloni, A., Heinz, S., Matteo, T., 2003, MNRAS, 345, 1057

Merloni, A., Heinz, S., 2007, MNRAS, 381, 589 (MH07)

Moderski, R., Sikora, M., Lasota, J. P., 1997, in "*Relativistic Jets in AGNs*" eds.M. Ostrowski, M. Sikora, G. Madejski & M. Belgelman, Krakow, p.110; [Astro-phy/0707.1914v]

Narayan, R., Yi, I. 1994, ApJ, 428, L13

Narayan, R., Yi, I., 1995, ApJ, 452, 710

Narayan, R., 2002, in Chui C. K., Sunyaev, R., Churazov, E., eds, Proc. MPA/ESO/, Lighthouses of the Universe: The Most Luminous Celestial Objects and Their Use for Cosmology. Springer-Verlag, Berlin, p. 405

Narayan, R. 2005, Ap&SS, 300, 177

Narayan, R., McClintock J. E., 2008, New Astron. Rev., 51, 733

Nemmen, R. S., et al. 2007, MNRAS, 377, 1652

Reynolds, C. S., Fabian A. C., Celotti, A., Rees, M. J., 1996, MNRAS, 283, 873

Spruit, H. C., 1996, NATO ASIC Proc. 477: Evolutionary Processes in Binary Stars, 249; see astro-ph/9602022

Urry, C. M., Padovani, P., 1995, PASP, 107, 803

Wang, D. X., Ye Y. C., Ma, R. Y. 2004, New Astron., 9, 585 (W04)

Willott, C. J. et al. 1999, MNRAS, 309, 1017

Wold, M., Lacy, M., Armus, L., 2007, A&A, 470, 531 (WLA07)

Wu, Q. W., Yuan, F., Cao, X. W., 2007, ApJ, 669, 96

Wu, Q.W., Cao, X.W., 2008, ApJ, 687, 156 (WC08)

Xie, F. G., Yuan, F., 2008, ApJ, 681, 499

Yuan, F. 2007, ASP Conf. Ser. 373, The Central Engine of Active Galactic Nuclei, ed. L. C. Ho and J.-M. Wang (San Francisco), 95

Yuan, F., Ma, R.Y., Narayan, R., 2008, ApJ, 679, 984 (YMN08)

Young, S. et al., 2007, Nature, 450, 74

A APPENDIX A: DERIVATION OF EQUATION (6)

Following Wang et al. (2004, hereafter W04), we express the Poynting energy flux S_E as

$$S_E = \frac{\Delta P_{EM}}{2\pi r \Delta r} \tag{A.1}$$

where ΔP_{EM} is the electromagnetic power extracted from ADAF between two adjacent magnetic surfaces. By invoking an equivalent circuit given by W04 ΔP_{EM} is written as

$$\Delta P_{EM} = \left(\Delta\varepsilon/\Delta Z_A\right)^2 \Delta Z_A, \tag{A.2}$$

where $\Delta\varepsilon$ is the electromotive force in the equivalent circuit, and it reads

$$\Delta\varepsilon = -\left(\Delta\Psi/2\pi\right)\Omega, \tag{A.3}$$

and $\Delta\Psi = B_{ADAF}2\pi r dr$ is the magnetic flux between the two adjacent magnetic surfaces. In W04 the load resistance is assumed to be axisymmetric, being located evenly in a plane,

and ΔZ_A is the resistance between the two adjacent magnetic surfaces. The surface resistivity σ_L of the unknown load is assumed to obey the following relation,

$$\sigma_L = \alpha_Z\sigma_H = 4\pi\alpha_Z, \tag{A.4}$$

where α_Z is a parameter, and $\sigma_H = 4\pi = 377\ ohm$ is the surface resistivity of the BH horizon.

$$\Delta Z_A = 2\alpha_Z\frac{\Delta r}{r}, \tag{A.5}$$

Assuming $\alpha_Z = 1$ and incorporating equation (A.1)—(A.5), we derive equation (6) for the Poynting energy flux S_E.